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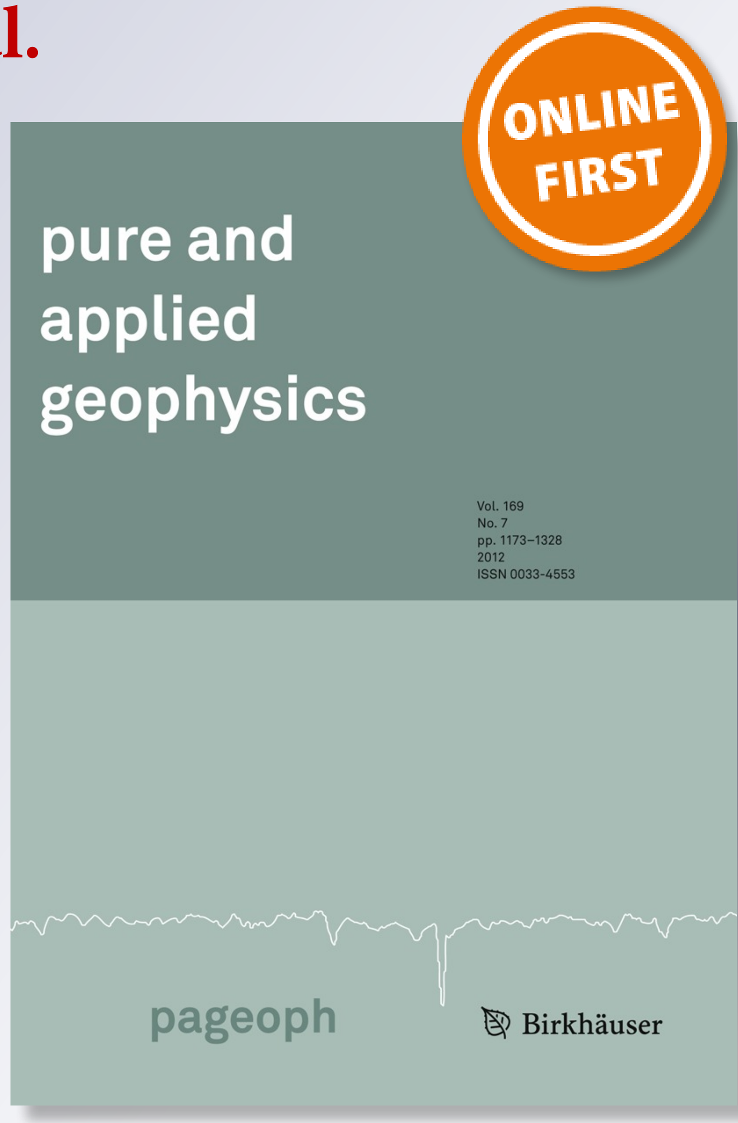

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Pure and Applied Geophysics

# Observations and Impacts from the 2010 Chilean and 2011 Japanese Tsunamis in California (USA)

Rick I. Wilson,[1] Amanda R. Admire,[2] Jose C. Borrero,[3,9] Lori A. Dengler,[2] Mark R. Legg,[4] Patrick Lynett,[5] Timothy P. McCrink,[1] Kevin M. Miller,[6] Andy Ritchie,[7] Kara Sterling,[8] and Paul M. Whitmore[8]

*Abstract*—The coast of California was significantly impacted by two recent teletsunami events, one originating off the coast of Chile on February 27, 2010 and the other off Japan on March 11, 2011. These tsunamis caused extensive inundation and damage along the coast of their respective source regions. For the 2010 tsunami, the NOAA West Coast/Alaska Tsunami Warning Center issued a state-wide Tsunami Advisory based on forecasted tsunami amplitudes ranging from 0.18 to 1.43 m with the highest amplitudes predicted for central and southern California. For the 2011 tsunami, a Tsunami Warning was issued north of Point Conception and a Tsunami Advisory south of that location, with forecasted amplitudes ranging from 0.3 to 2.5 m, the highest expected for Crescent City. Because both teletsunamis arrived during low tide, the potential for significant inundation of dry land was greatly reduced during both events. However, both events created rapid water-level fluctuations and strong currents within harbors and along beaches, causing extensive damage in a number of harbors and challenging emergency managers in coastal jurisdictions. Field personnel were deployed prior to each tsunami to observe and measure physical effects at the coast. Post-event survey teams and questionnaires were used to gather information from both a physical effects and emergency response perspective. During the 2010 tsunami, a maximum tsunami amplitude of 1.2 m was observed at Pismo Beach, and over $3-million worth of damage to boats and docks occurred in nearly a dozen harbors, most significantly in Santa Cruz, Ventura, Mission Bay, and northern Shelter Island in San Diego Bay. During the 2011 tsunami, the maximum amplitude was measured at 2.47 m in Crescent City Harbor with over $50-million in damage to two dozen harbors. Those most significantly affected were Crescent City, Noyo River, Santa Cruz, Moss Landing, and southern Shelter Island. During both events, people on docks and near the ocean became at risk to injury with one fatality occurring during the 2011 tsunami at the mouth of the Klamath River. Evaluations of maximum forecasted tsunami amplitudes indicate that the average percent error was 38 and 28 % for the 2010 and 2011 events, respectively. Due to these recent events, the California tsunami program is developing products that will help: (1) the maritime community better understand tsunami hazards within their harbors, as well as if and where boats should go offshore to be safe, and (2) emergency managers develop evacuation plans for relatively small "Warning" level events where extensive evacuation is not required. Because tsunami-induced currents were responsible for most of the damage in these two events, modeled current velocity estimates should be incorporated into future forecast products from the warning centers.

**Key words:** Tsunami, field observations, warning center, maritime, damage, California.

## 1. Introduction

California's 1,100-mile-long coastline is home to over one-million residents and tens of millions of visitors each year that are at risk to both local and distant tsunami hazards (California Seismic Safety Commission, 2005). There are 20 counties, 100 cities, and over 60 maritime communities that are vulnerable to tsunamis. Over 100 possible or confirmed tsunamis have been observed or recorded in California since 1800 (Lander *et al.*, 1993;

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National Geophysical Data Center, 2012). While the majority of these events were small and only detected by tide gauges, thirteen were large enough to cause damage and five events have caused deaths (Dengler, 2011; NGDC 2012). The most significant tsunami to impact California was the March 27, 1964 Alaska event, flooding 29 blocks of Crescent City and killing 13 people statewide.

Although there had been a history of damaging tsunamis, the public perception was that California faced only a moderate tsunami threat along most of its coast. This perception of tsunami risk began to change in 1992 when a magnitude ($M_w$) 7.2 earthquake in northern California produced a small local tsunami. Although the tsunami did not cause damage, it raised concerns and the level of awareness in the California about a potential near-source tsunami originating from the Cascadia Subduction Zone. The California Governor's Office of Emergency Services convened a Tsunami Hazard Mitigation Workshop in 1997, comprised of local, state and federal agencies. Even though participating local jurisdictions were aware of the tsunami threat, most had done little tsunami specific evacuation, mitigation, preparedness, response or recovery planning. The workshop participants identified a critical need for the development and distribution of up-to-date inundation maps to the communities at risk, as well as the development of guidance on how to use the maps for local government. Representatives of coastal counties were brought together to identify and prioritize the areas along the California coastline to be mapped during the initial phase of the state tsunami program. With funding from the National Tsunami Hazard Mitigation Program (NTHMP) of the National Oceanic and Atmospheric Agency (NOAA) work began on identifying California's tsunami threat. By 2003 an initial set of course-grid tsunami inundation maps had been developed. The devastating 2004 Indian Ocean tsunami increased tsunami awareness, and improved funding opportunities for and planned activities by the State of California tsunami program.

Several recent events have focused additional attention on California's tsunami hazard since the Indian Ocean tsunami. In June 2005, a $M_w$ 7.2 earthquake located 90 miles off the Northern California coast, triggered a Tsunami Warning for the entire West Coast of the United States and revealed numerous weaknesses in California's tsunami preparedness (California Seismic Safety Commission, 2005; Rabinovich *et al.*, 2006). In November 2006, Tsunami Alert bulletins were issued for the Pacific after a $M_w$ 8.3 earthquake in the Kuril Islands. The alerts were cancelled before waves were due to arrive in California but two Northern California counties chose to conduct limited evacuations of the beach and harbor areas based on informal dialog with the West Coast/Alaska Tsunami Warning Center (WC/ATWC) (Dengler *et al.*, 2009). Strong currents produced by the tsunami caused an estimated $20 million in damages to docks at Crescent City harbor in Del Norte County, but the evacuations prevented injuries.

As a result of the 2006 Kuril tsunami event, the WC/ATWC changed the definition of an "Advisory" bulletin from an alert that meant a warning has been issued for a distant section of the ocean basin, to an alert signifying localized threat of strong currents in harbors, like the impacts observed in Crescent City (Whitmore *et al.*, 2008). The first time the new Advisory definition was used in California was September 29, 2009 after the $M_w$ 8.1 Samoa earthquake (Wilson *et al.*, 2010). Although no damage was reported from this tsunami, moderate currents were generated in a number of harbors statewide causing problems for some boaters and harbor personnel. In response to the alerts from WC/ATWC, the state activated its emergency operation centers to coordinate specific messaging information, relay this to coastal jurisdictions in coordinated fashion, and address any emergency assistance needs arising at the local level. Both the 2006 and 2009 tsunamis provided emergency managers in maritime communities and other coastal jurisdictions an experience to draw from for more recent events. This paper focuses on the February 27, 2010 tsunami from Chile and the March 11, 2011 tsunami from Japan including:

- Pre-tsunami emergency preparedness and response actions of the WC/ATWC and state and local emergency managers;
- The physical effects (tsunami amplitudes, currents, damage, etc.) from field observations made during the tsunami and post-tsunami field surveys and questionnaires;

- The accuracy of tsunami forecasts and the impacts to the maritime communities from both events; and,
- Lessons learned and a plan for addressing existing issues within the emergency response and maritime communities.

## 2. *Recent Tsunamis in California*

The 2010 Chile and 2011 Japan tsunamis were the most significant tsunamis to hit California statewide since 1964. Both tsunamis were of sufficient size for the WC/ATWC to put portions of the state into an alert level of either "Advisory" (0.3–1 m forecast amplitudes) or "Warning" (forecast amplitudes greater than 1 m). Both events fully activated the emergency response system in California with emergency operation centers opened at both the state and local levels to coordinate information, advise on emergency response measures, and provide life, safety and recovery assistance as needed. Each event was also responsible for millions of dollars of damage in a number of harbors (Fig. 1).

Information presented within this paper was collected by prepositioned tsunami and post-tsunami field personnel who were part of the California Tsunami Clearinghouse, created in the aftermath of the 2009 Samoa tsunami (Wilson *et al.*, 2011a). Because there was a significant time delay of at least 10 h between tsunami generation and when surges arrived along California's shore, field response teams were deployed to predetermined, safe locations to observe both tsunamis in real-time and gather perishable field data immediately following these events. Within a week after the tsunamis, questionnaires asking about physical effects and response activities were sent to coastal jurisdictions, including maritime communities, State Parks/Beaches, and local governmental agencies. Teams of geoscientists were also sent to interview personnel in these jurisdictions to gather pertinent information about the tsunami not previously collected. Much of the information collected from the field surveys, questionnaires, and interviews is summarized within this paper or in Table 1 for both the 2010 and 2011 tsunamis.

The authors note that there are conflicting accounts of the accuracy of these eyewitness observations of current velocities, and care should be taken on these reports. When eyewitness accounts from Wilson *et al.* (2011b) are compared to video camera estimates, the current speeds provided by eyewitnesses at some locations were overestimated by as much as twice the amount of the currents measured in the videos (Admire *et al.*, 2011). Lynett *et al.* (2012) found that eyewitness velocity estimates in some cases were accurate when compared to video and modeling analysis results. Eyewitnesses may be looking at micro-conditions around sharp corners or docks where high currents occur within the harbors. Clearly, the accuracy of observed velocities depends on the experience of the eyewitness, and ideally the currents should be compared to video analysis results, which is not possible in all cases. For this reason, current velocity estimates will only be reported if they are provided by experienced observers, such as harbor masters, or clearly validated by video analysis.

### 2.1. *February 27, 2010 Tsunami*

On February 26th, 2010, at 2234 PDT, a $M_w$ 8.8 earthquake struck the Maule region of central Chile. The earthquake was generated along the plate boundary where the Nazca Plate is being subducted under the South American Plate, approximately 300 km north of the 1960 $M_w$ 9.5 Great Chilean earthquake. Locally, damage from the Maule earthquake was significant to older buildings and buildings with limited reinforcement. A large tsunami was generated, causing 156 fatalities and severe damage to coastal towns and port facilities in Chile (NGDC, 2012; Fritz *et al.*, 2011).

At 0255 PDT, a little over 4 hours after the Maule earthquake origin time, the WC/ATWC placed the entire California coast in a Tsunami Advisory, with forecasted maximum tsunami amplitudes ranging from approximately 0.3–1.4 m, and cautioned that strong currents in bays and harbors could occur. Hourly conference calls were held with emergency managers in the county operational areas and most counties cleared beaches and limited access to harbor areas. The highest amplitudes were predicted for San Luis Obispo County and areas south. The tsunami

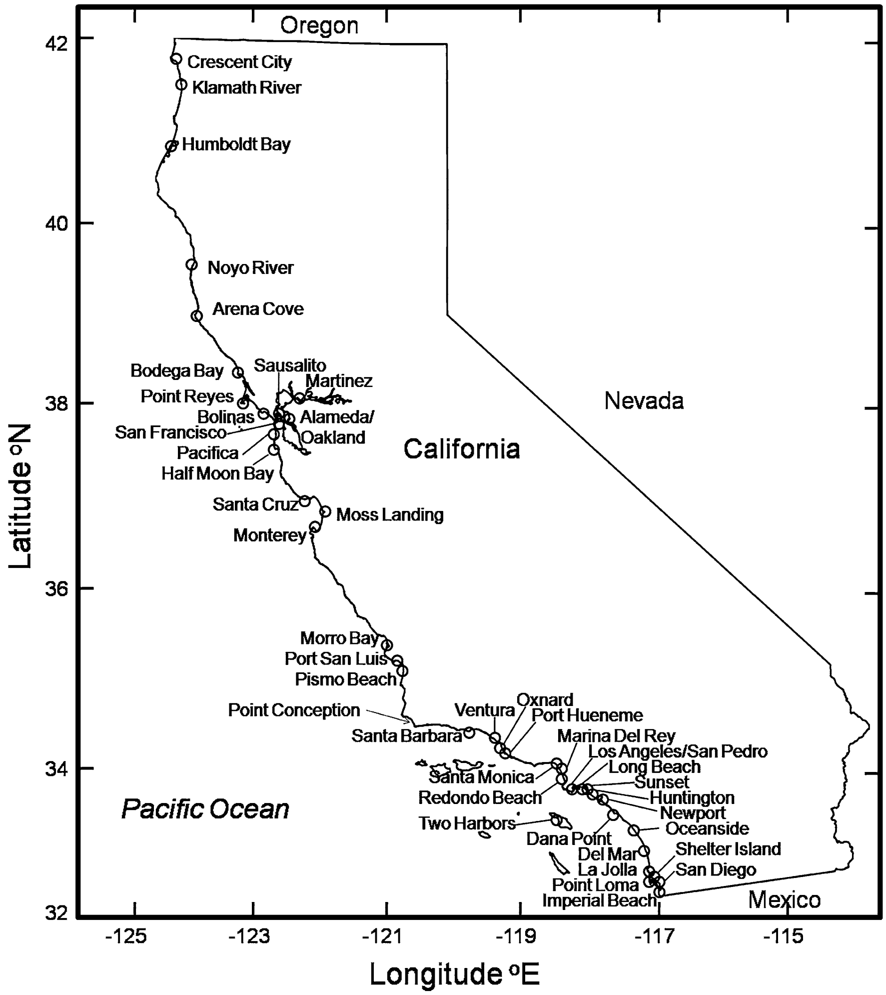


Figure 1
Map of California showing locations of interest during the February 27, 2010 and March 11, 2011 tsunamis

initially arrived at San Diego at 1202 PDT on February 27, and moved progressively up the coast over the next hour and a half. Fortunately, the peak tsunami amplitudes occurred near low tide, reducing the potential for inundation of dry land (Wilson *et al.*, 2010). However, despite the relatively low absolute water levels, strong currents were generated inside harbors and bays.

Table 1 provides a summary of forecasted tsunami amplitudes, measured or observed amplitudes, and a description of the damage that occurred in harbors and bays. Peak amplitudes at tide gauge locations in the state ranged from 0.12 m to a high of 0.91 m at Santa Barbara. As forecasted by the WC/ATWC, the largest tidal fluctuation (peak to trough) of 2–2.5 m and about 1.2 m maximum amplitude was observed along the central coast near Pismo Beach. Surging water and rapid water-level fluctuations in many harbors and bays produced strong currents reportedly up to 8 m/sec at some locations, though these are based on eyewitness observations that could be exaggerated when compared to video analysis (Admire *et al.*, 2011). Currents in excess of 2 m/sec are known to cause damage to piers and docks (Uslu *et al.*, 2010) and, based on the level of damage, strong currents in excess of 2 m/sec likely occurred. Strong tsunami currents caused minor to moderate damage to docks, boats, and harbor infrastructure in at least a dozen locations, mostly in southern California. At most locations, the peak surges were

Table 1

*Shows forecasted and observed arrival times and tsunami amplitudes as well as a summary of damage for both the February 27, 2010 and March 11, 2011 tsunamis in California*

| Harbors, ports, bays, and docks surveyed (from north to south) | First arrival times | | | | Maximum tsunami amplitudes (meters) | | | | Reported damage or other effects from tsunami | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Feb. 27, 2010 | | March 11, 2011 | | Feb. 27, 2010 | | March 11, 2011 | | Feb. 27, 2010 | March 11, 2011 |
| | Forecasted (PDT) | Observed tide gauges or estimated by others* (PDT) | Forecasted (PST) | Observed tide gauge or estimated by others* (PST) | Forecasted | Observed tide gauge or estimated by others* | Forecasted | Observed tide gauge or estimated by others* | | |
| Crescent City | 1340 | 1346 | 0723 | 0734 | 0.61 | 0.64 | 2.50 | 2.47 | NDR | Near complete destruction of small boat harbor ($20 M) |
| Klamath River | | | | | | | 2.36 | | NDR | One fatality (drowning) |
| Humboldt Bay | 1336 | 1333 | 0722 | 0734 | 0.2 | 0.23 | 1.33 | 0.97 | NDR | NDR |
| Noyo River | | | | | | | | 0.8–1.0* | NDR | Major damage to docks/boats ($4 M) |
| Arena Cove | 1248 | 1304 | 0726 | 0729 | 0.49 | 0.39 | 1.30 | 1.74 | NDR | NDR |
| Bodega Bay | | | | | | | 0.97 | 0.5–0.7* | NDR | NDR |
| Point Reyes | 1259 | 1259 | 0739 | 0746 | 0.46 | | 0.63 | 1.35 | NDR | NDR |
| Bolinas | | | | | | | | 0.7–0.9* | NDR | NDR |
| Sausalito | | | | | | | 0.37 | 1.2–1.5* | NDR | Houseboat damage; broken sewer line |
| Martinez | | | | 0950* | | | | 0.06 | NDR | NDR |
| Alameda/Oakland | 1344 | 1345 | | 0836 | 0.18 | 0.12 | 0.29 | 0.51 | NDR | Minor damage at nearby Berkeley Marina |
| San Francisco | 1320 | 1326 | 0808 | 0812 | 0.22 | 0.32 | 0.73 | 0.62 | NDR | Two piles broken |
| Pacifica | | | | | | | 0.85 | 0.8–1.0* | NDR | NDR |
| Half Moon Bay | | | | | 0.96 | 0.6* | 0.92 | 0.7* | NDR | NDR |
| Santa Cruz | | | | | 0.51 | 0.9* | 1.01 | 1.6–1.9* | Minor damage to boats and harbor infrastructure | Multiple docks destroyed, 14 boats sunk ($28 M) |
| Moss Landing | | | | | | 0.3* | | 2.0* | NDR | 200 piles damaged ($1.75 M) |

**Table 1** *continued*

| Harbors, ports, bays, and docks surveyed (from north to south) | First arrival times | | | | Maximum tsunami amplitudes (meters) | | | | Reported damage or other effects from tsunami | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Feb. 27, 2010 | | March 11, 2011 | | Feb. 27, 2010 | | March 11, 2011 | | Feb. 27, 2010 | March 11, 2011 |
| | Forecasted (PDT) | Observed tide gauges or estimated by others* (PDT) | Forecasted (PST) | Observed tide gauge or estimated by others* (PST) | Forecasted | Observed tide gauge or estimated by others* | Forecasted | Observed tide gauge or estimated by others* | | |
| Monterey | 1231 | 1243 | 0744 | 0748 | 0.45 | 0.36 | 0.52 | 0.70 | NDR | NDR |
| Morro Bay | | | | 0800 | 0.82 | 0.5* | 1.18 | 1.6 | NDR | Damage to several docks and boats ($500 k) |
| Port San Luis | | | 0803 | 0810 | 0.84 | 0.8* | 2.14 | 2.02 | NDR | NDR |
| Pismo Beach | | | | | 1.43 | 0.9–1.2* | 0.73 | 0.7–1.0* | NDR | NDR |
| Santa Barbara | 1230 | 1231 | 0817 | 0827 | 0.75 | 0.91 | 0.48 | 1.02 | Minor damage to dredging equipment | Damage to barges and boats ($70 k) |
| Ventura | | | | | | 0.6–0.9* | 0.88 | 1.3* | Over 20 docks damaged; buoys moved ($300–500 k) | Damage to dock and number of boats ($150 k) |
| Oxnard | | | | 0830* | | 1.0* | | 0.9–1.2* | Dock damage from large boat wake | Minor damage to docks |
| Port Hueneme | | | | | | 0.5–0.7* | | 1.2–1.4* | NDR | NDR |
| Santa Monica | 1225 | 1225 | 0831 | 0843 | 1.18 | 0.64 | 0.84 | 0.85 | NDR | NDR |
| Marina Del Rey | | | | 0830* | | 0.1* | | 0.9–1.0* | Minor damage to dock | Minor damage to docks; dinghies sunk |
| Redondo Beach | | | | | | | 0.65 | 0.6–0.7* | NDR | Dock destroyed; five boats damaged |
| Two Harbors/Catalina | | | | | | 0.6–0.9* | | | Minor damage to several docks | Damage to several docks and 10 boats |
| Los Angeles/San Pedro | 1215 | 1215 | 0832 | 0840 | 0.77 | 0.42 | 0.39 | 0.49 | Minor damage to docks and marine infrastructure | Minor damage to docks and boats |
| Long Beach | | | | | | | | | NDR | Minor damage to docks and boats |
| Sunset | | | | | | 0.3–0.5* | | | NDR | NDR |
| Huntington | | | | | | | 0.71 | | NDR | Boat pulled off mooring |

**Table 1** *continued*

| Harbors, ports, bays, and docks surveyed (from north to south) | First arrival times | | | | Maximum tsunami amplitudes (meters) | | | | Reported damage or other effects from tsunami | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Feb. 27, 2010 | | March 11, 2011 | | Feb. 27, 2010 | | March 11, 2011 | | Feb. 27, 2010 | March 11, 2011 |
| | Forecasted (PDT) | Observed tide gauges or estimated by others* (PDT) | Forecasted (PST) | Observed tide gauge or estimated by others* (PST) | Forecasted | Observed tide gauge or estimated by others* | Forecasted | Observed tide gauge or estimated by others* | | |
| Newport | | | | 0846* | | 0.5* | | 0.3* | NDR | NDR |
| Dana Point | | | | 0830* | | 0.5–0.7* | | 0.6* | Bait barge severed | Pylon damaged when hit by boat |
| Oceanside | | | | | | 0.6* | | 0.5* | Minor dock damage; several buoys carried to sea; boat trailer swamped | NDR |
| Del Mar | | | | | | | 0.58 | 0.9* | NDR | NDR |
| La Jolla | 1202 | 1202 | 0841 | 0847 | 0.84 | 0.60 | 0.70 | 0.9* | NDR | NDR |
| Mission Bay | | | | | | | | | Small sailboat swamped trying to leave harbor; buoys moved | Dock destroyed, 13 boats damaged ($136 k) |
| Point Loma | | | | | | | 0.69 | 0.5 | NDR | NDR |
| Shelter Island, San Diego Bay | | | | | | 0.9–1.2* | | 0.8* | North Island: moderate damage to docks, concrete piers, and boats | South Island: a boat sunk and there was damage to dock |
| San Diego Bay/ Interior | 1204 | 1208 | | | 0.27 | 0.40 | 0.35 | 0.63 | NDR | NDR |
| Imperial Beach | | | | 0930* | | | 0.78 | 0.5* | NDR | NDR |

*NDR* no damage reported; damage estimates in parentheses

The asterisk indicates values were obtained from observers (not tide gauges) recorded within the first 2 h. For some locations, including Crescent City and Santa Barbara, the largest surge occurred 5 h after the initial onset. At many locations, the tsunami activity lasted for more than a day. In some areas, such as Huntington Beach in southern California, the tsunami surges exacerbated ambient flooding from severe storm activity.

#### *2.1.1 Most Impacted Areas*

The region north of Santa Cruz experienced moderate currents within harbors but no damage was reported. The following summarizes observations, effects, and damage from the tsunami at a number of locations from Santa Cruz south.

*2.1.1.1 Santa Cruz* Maximum peak-to-trough tidal fluctuations of 2.2 m were measured, creating strong currents reported by the harbor master to be approximately 5 m/sec in the narrow portions of the harbor (Wilson *et al.*, 2010). Just prior to the arrival of the tsunami, several large charter boats left the harbor and stayed out for 6 h because reentry into the harbor was too difficult due to the strong currents. The harbor master felt that moving these large boats out of the harbor may have reduced the potential for damage to docks. Two other boats did break free from their moorings and caused minor damage in collisions with other boats and harbor infrastructure (Fig. 2a). Significant drawdown caused shoaling near the entrance and the far back end of the harbor.

*2.1.1.2 Santa Barbara* The highest measured amplitude in the state (0.91 m) occurred 5 h after first wave arrival. Strong currents up to 4.5 m/sec were reported by the harbor master within narrow channels and the mouth of the harbor entrance (Wilson *et al.*, 2010). The harbor master reported that 30 min prior to the first surge arrival, he received a message that the Tsunami Alert was being upgraded to a Warning, with tsunami amplitudes of up to 2–3 m. It was unclear how this incorrect information was generated but it was thought that alert messages were misinterpreted from the PTWC, which at that time had a different definition of an "Advisory." Although this information was incorrect for California, Santa Barbara and several other maritime communities indicated they reacted with a higher urgency than they had earlier in their response. Nevertheless, boats that went offshore before the tsunamis tried to reenter the harbor and almost ran aground because of the strong currents.

*2.1.1.3 Ventura* Ventura Harbor sustained the most significant damage from the 2010 tsunami for California. At least 20 docks were damaged in the Ventura Keys, a section of the harbor with narrow, shallow channels which likely amplified tsunami currents in the area (Fig. 2b). The harbor master reported that retreating tsunami currents approached 6–7 m/sec (Wilson *et al.*, 2010). According to the harbor master, damage to the docks was estimated to be between $300,000 and $500,000, though strong tsunami currents caused scour at the mouth of the harbor and resulted in an apparent $100,000 in dredging savings.

*2.1.1.4 Mission Bay* Because the entrance to the Bay is narrow, strong currents were generated at the mouth of the Bay. During the tsunami, an 8 m-long sailboat attempted to leave the harbor during the ebb flow of the tsunami. A combination of the strong retreating tsunami currents and wave activity from a storm offshore produced 3 m standing waves at the Bay entrance, swamping the boat and initiating a rescue of its two passengers by lifeguards. The boat was damaged beyond repair. A security video camera from the nearby lifeguard station with night vision capability recorded on-going strong surges and currents after 2100 PDT on February 27th, 9 h after first surge arrival.

*2.1.1.5 Shelter Island, San Diego Bay* Peak tsunami amplitudes were observed to be about one meter at the north end of Shelter Island. Extreme currents were generated around the northern tip of the Island likely because it was the most direct flow line in and out of the America's Cup Harbor to the mouth of the bay to the south. On-line photos and video captured very strong currents approaching 5 m/sec destroying part of a dock at the end of the Island as it enters into the harbor (Fig. 2c, d). This point on the north part of the island likely became the focus of strong currents because it was shortest

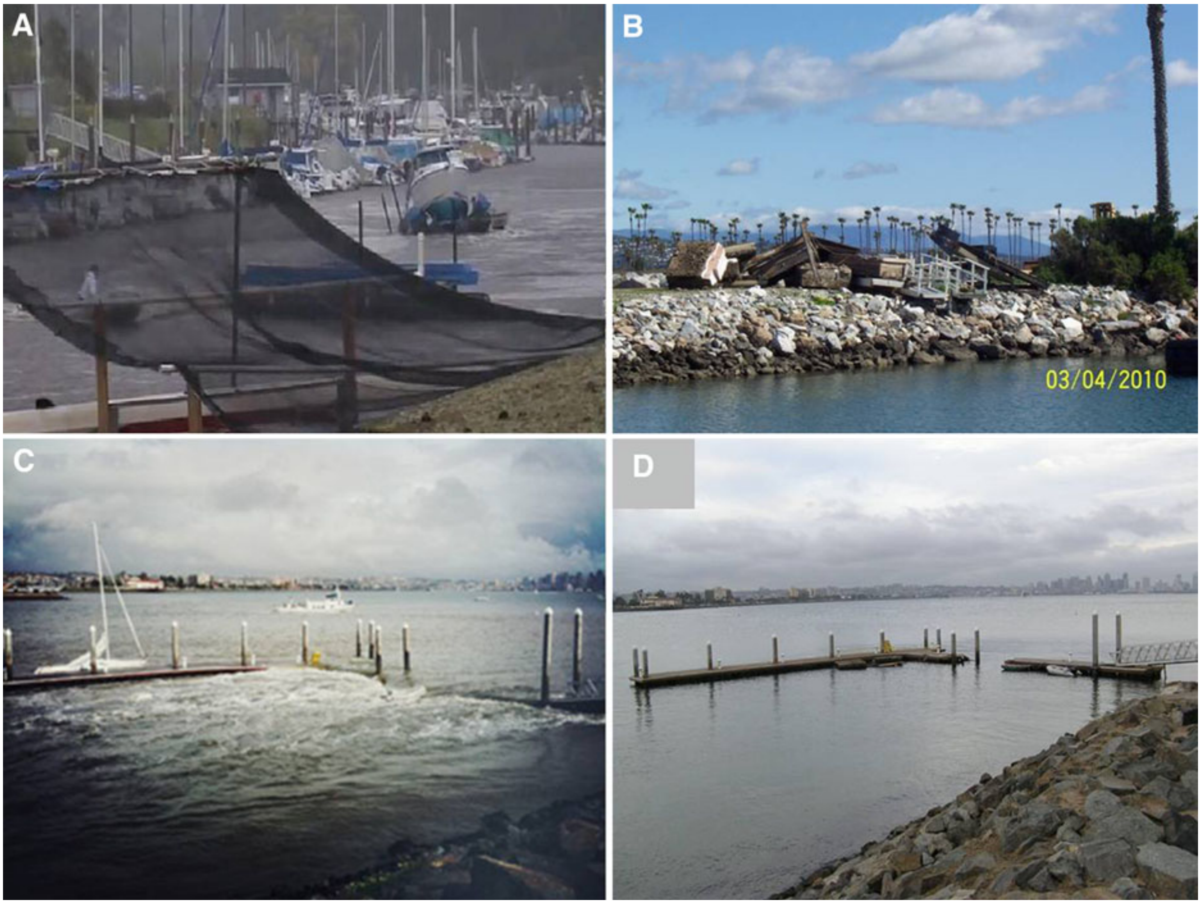


Figure 2
A through 2D: photos from the February 27, 2010 tsunami in California. Figure 2a is a still image of a boat that floats loose during the tsunami in Santa Cruz Harbor (source: YouTube video). Figure 2b photo of docks damaged during the 2010 tsunami in Ventura Harbor (source: Dale Carnathan). Figure 2c and d are pictures showing flooding and damage to dock taken during and after the 2010 tsunami, northern Shelter Island, San Diego Bay (sources: Fig. 2c is still image from YouTube video; Fig. 2d is by Rick Wilson)

path for water flowing in and out of the harbor. Within the harbor, it was reported that the tsunami caused a large, 25-m-long, 100-ton fishing boat moored to a wooden dock to tear this dock from the concrete piles to which it was secured. The boat was recovered before it damaged other nearby boats or docks. Barberopoulou *et al.* (2011a) confirmed the large current velocities at Shelter Island using numerical tsunami modeling.

### 2.1.2 Lessons Learned

California tsunami preparedness programs at the federal, state, and local level identified a number of weaknesses after the Chile tsunami that led to changes in outreach emphasis and activities:

- Federal, state, and local emergency managers identified a need to clarify what a "Tsunami Advisory" means to their constituents. Tsunami messaging for an "Advisory" was made more consistent between the WC/ATWC and the Pacific Tsunami Warning Center (PTWC). The State of California tsunami program held over a dozen workshops statewide to educate local jurisdictions about their tsunami hazard and provide guidance for the development of a more consistent response plans between adjacent communities. Local planners updated their local emergency response plans, improving their inter-agency communication and increasing their outreach capabilities.
- Federal and state programs improved tsunami response communication and coordination with

organizations such as the Coast Guard and California State Parks, all with significant coastal jurisdictional responsibilities and control. State Parks are responsible for managing one-third of California's coastal lands/beaches, and the Coast Guard is the primary contact for emergency response within the maritime community. Representatives from both organizations were added to the emergency response communication protocol when a tsunami Advisory or Warning is initiated.

- Maritime communities discovered that an "Advisory" level event with sub-meter amplitudes could still significantly challenge their response and impact their facilities because of strong tsunami currents. Each of the harbor masters that were interviewed mentioned that the water-level fluctuations and currents were more dramatic than they had expected, and that improved education of their staff and the boating communities overall about these hazards was vital to saving lives and property. For example, based on the 2006 Kuril Island tsunami and this 2010 tsunami, the fishing fleet at Crescent City worked with the Redwood Coast Tsunami Work Group and NOAA to evaluate and practice boat evacuation prior to a tsunami. In addition, a number of maritime communities developed plans to evacuate or move large boats away from areas of expected strong tsunami currents. A number of harbors developed outreach materials to educate their boating community about tsunamis, specifically their hazard currents and length of activity, and preparedness for evacuating boats offshore.
- The 2010 tsunami provided incentives to improve tsunami education and outreach activities and heightened tsunami awareness throughout the state. Public interest and community preparedness activities increased significantly after the event.

### 2.2. *March 11, 2011 Tsunami*

On March 11, 2011, at 05:46:24 UTC (0246 h in Japan; and 2146 h on March 10th in California), a Mw 9.0 earthquake struck the eastern coast of the Tohoku region, northern Honshu Island in Japan. A large, destructive tsunami was generated locally, with tsunami heights up to 39 m and flooding that traveled over 10 km inland in places (Tohoku Earthquake Tsunami Joint Survey Group, 2011). As of March 5, 2012, the Japanese National Police Agency (2012) indicated that 15,854 people in Japan are confirmed dead and another 3,274 remain missing. More than 90 % of the fatalities from this event were caused by the tsunami (SEEDS Asia, 2011).

At 0051 PST, a little over 3 h after the Tohoku earthquake origin time, the WC/ATWC placed the California coast north of Point Conception in a Tsunami Warning, and the coast south of the Point Conception in a Tsunami Advisory. The range of Warning/Advisory forecast tsunami amplitudes varied from 0.3 to 2.5 m, with the highest surge forecasted for Crescent City. Hourly conference calls were held with the county operational areas and some communities within the Warning-level area began evacuation procedures.

The tsunami arrived at Crescent City in northern California at 0730 PST, on March 11, and moved southward along the coast over the next hour and a half (Table 1). Peak amplitudes at tide gauge locations in the state ranged from a low of 0.15 m to a high of 2.47 m at Crescent City. At most locations, the strongest surges were recorded within the first 5 h. Because the largest surges arrived at low tide, only minor inundation outside of harbor and river settings occurred. Several tide gauges, for example Crescent City and Santa Barbara, recorded large surges nearly 15 h after the initial onset when the tide was high. At Crescent City, the only on-land flooding occurred at 0200 on March 12, nearly 20 h after the initial onset when high tide conditions occurred. These late surges created hazardous conditions and resulted in additional localized damage. Very strong currents and large water-level fluctuations (over 4.5 m peak-to-trough in Crescent City) caused significant damage to two-dozen harbors throughout the State. There was one fatality in California (and the West Coast of the US) when a man too close to dangerous tsunami surges was swept away and drowned at the mouth of the Klamath River in northern California. The state again activated its emergency operation centers to coordinate information and emergency response measures with coastal jurisdictions and the WC/ATWC.

Following the tsunami, a State of Emergency was proclaimed by Governor Brown for seven counties, and a Major Federal Disaster was declared by President Obama for three counties (Del Norte, Santa Cruz, and Monterey) because of the significant damage to harbors in Crescent City, Santa Cruz, and Moss Landing. The Federal Disaster damage estimate was about \$50 M but post-event field assessments and interviews with harbor masters put the unofficial estimate closer to \$100 M; in either case, this was the largest, most damaging tsunami to hit California since 1964 (Wilson *et al.*, 2011b).

### *2.2.1 Most Impacted Areas*

California locations that experienced damage in the March 11 tsunami are summarized in Table 1. The following section describes effects and damage from the tsunami at the most severely impacted locations.

*2.2.1.1 Crescent City* The most severe tsunami effects in the state occurred at Crescent City, a harbor well known for being vulnerable to tsunamis due to the offshore bathymetry and the configuration of the small-boat basin (Dengler *et al.*, 2008; Kowalik *et al.*, 2008; Horrillo *et al.*, 2008). Maximum tsunami amplitudes of 2.5 m were forecasted for Crescent City. Boat owners were notified beginning at the 0100 h on March 11 and 40 of the 45 boat commercial fishing fleet safely exited the harbor between the hours of 0200 and 0600. Sirens were sounded and door-to-door evacuations began at 4 am. School buses were used to assist with mobility-impaired residents. Within the first 2 h of the tsunami activity, the tide gauge recorded a peak amplitude of 2.47 m, which fortunately occurred at low tide producing minimal inundation of dry land. Figure 3 (from Wilson *et al.*, 2012) illustrates the incoming erosional and non-erosional flow patterns, current velocity estimates from video analysis, and areas of sediment deposition and erosion within the harbor. Strong currents were observed throughout the outer harbor and small-boat basin, with video analysis indicating peak currents of 4.5 m/sec at the mouth of the basin (Admire *et al.*, 2011). The highest absolute water levels occurred between midnight and 0200 on March 12 when the peak tide reached 2 m and the tsunami amplitudes were still close to 1.5 m. Some overland flooding was observed in the recreational vehicle park near the mouth of Elk River and at Citizens Dock. Strong tsunami currents prevented emergency personnel from working in the boat basin for 2 days and tsunami oscillations persisted on the tide gauge for 6 days. All docks within the small boat basin were heavily damaged or destroyed during the tsunami (Fig. 4a). Although 40 boats exited the harbor prior to the tsunami, 16 boats were sunk and 47 were damaged according to the Northern California Tsunami Unified Command (2011). The boats that left the harbor stayed offshore until the late afternoon on March 11. Most of the boats then sought harbor in Humboldt Bay, about 100 km to the south. A few boats had insufficient fuel to travel that far and were forced to anchor in the outer harbor in Crescent City. Overall, the harbor sustained an additional \$20 M of damage beyond that of the 2006 Kuril Islands tsunami, which had still not been repaired because of delays in funding (Rich Young, personal communication). Sediment that had been deposited in the harbor by the tsunami, some 150,000 $m^3$ of material, took over 10 months to remove because of delays in permitting and sampling of the material deposited by the tsunami (Weston Solutions Inc., 2011; Wilson *et al.*, 2012).

*2.2.1.2 Noyo River* Strong tsunami currents and bores traveled along the narrow Noyo River near Fort Bragg. Two marinas, one of which is approximately 1.5 km from the mouth of the river, sustained about \$4 M worth of damage to docks and infrastructure. Most of the damage was confined to the area near the narrow openings of both harbors to the river. The harbor masters indicated the damage would have been worse if some of the larger fishing boats had not evacuated offshore prior to the tsunami's arrival. Many smaller boats were unable to leave for deep water before the tsunami arrived due to the large swells breaking at the entrance to the harbor that morning.

*2.2.1.3 San Francisco Bay* Although San Francisco Bay is protected by a narrow opening to the ocean at the Golden Gate, larger than expected tsunami amplitudes were observed ranging from 0.35 m in

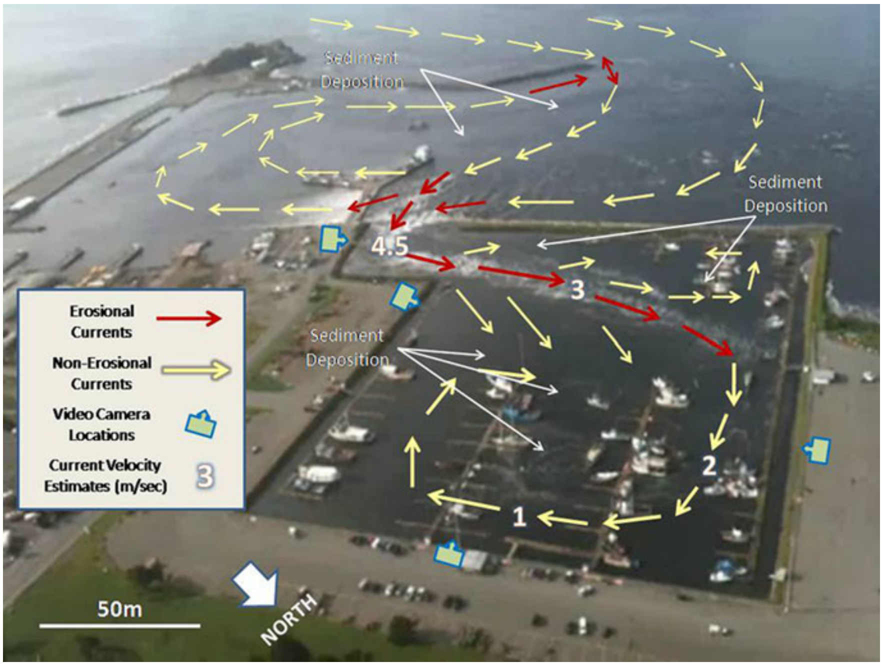


Figure 3
Tsunami flow-regime map for Crescent City Harbor, from Wilson *et al.* (2012). Current directions and velocities, and areas of sediment erosion and deposition are based on observations of the various (30) ground-level and aerial video, pre- and post-tsunami bathymetry, and sediment analyses

Richmond to about 1.2–1.5 m near Sausalito. Several tsunami bores were observed traveling across the Bay in the first several hours after first tsunami arrival (Fig. 4b). Harbors and marinas in San Francisco, Sausalito, and Berkeley reported minor damage to docks and boats due to moderate currents and large water-level fluctuations.

*2.2.1.4 Santa Cruz* Though no tide gauge exists within Santa Cruz Harbor, peak tsunami amplitudes of 1.6–1.9 m were observed in the harbor constrictions by pre-positioned observers. Figure 5 (from Wilson *et al.*, 2012) illustrates the incoming tsunami flow patterns, current velocity estimates from video analysis, and areas of sediment deposition and erosion within the harbor. Approximately 3 hours after first tsunami arrival, several large, fast-moving bores were observed moving to the far back of the harbor, causing dramatic buckling of docks where the harbor narrows (Fig. 4c). Based on preliminary estimates from video analysis, these bores were traveling up to 7 m/sec in the back part of the harbor (Wilson *et al.*, 2012). The overall long, rectangular shape of the harbor likely amplified incoming surges causing the strong currents and the bores described. The overall damage to the harbor was more than $28 M, with 14 boats sunk and dozens of other boats damaged (Mesiti-Miller Engineering, Inc., 2011; Chuck Izenstark, personal communication). Of the harbor's 29 docks, 23 docks sustained significant damage ranging from severe float cracking to complete dock destruction. As of May 2012, repair work and dredging of tsunami-related sedimentation within the harbor was ongoing.

*2.2.1.5 Moss Landing* Located at the mouth of the Elkhorn Slough in Monterey Bay, Moss Landing received tsunami tidal fluctuations (peak-to-trough) up to 2 m several hours after first surge arrival. Strong currents were observed near the mouth of the slough and within the marina areas. The rapid water-level fluctuations caused the metal rings on the docks to shear the 200 wooden piles to which they were attached, resulting in $1.75 M in estimated damage. Because of this damage, Monterey County was designated a Federal Disaster area several months after the tsunami.


Figure 4
A through 4D: photos from the March 11, 2011 tsunami in California. Figure 4a is a still image aerial view of heavy damage within Crescent City small boat basin (source: YouTube video). Figure 4b is a still image of a tsunami bore within east San Francisco Bay (source: YouTube video). Figure 4c is a still image of tsunami bore and damage in Santa Cruz Harbor (source: YouTube video). Figure 4d is a still image of boat sinking and damage to docks in southern Shelter Island, San Diego Bay (source: San Diego Police video camera)

*2.2.1.6 Morro Bay* A tide gauge installed and monitored by California Polytechnic State University at San Luis Obispo measured fluctuations (peak-to-trough) of about 2.5 m and a peak tsunami amplitude 1.6 m. The harbor master indicated that current velocities may have approached 7 m/sec in confined parts of the harbor causing damage to several boats, docks, and maritime infrastructure (Wilson *et al.*, 2011a, b).

*2.2.1.7 Ventura* Moderately damaged during the 2010 tsunami, Ventura Harbor sustained less damage during the March 11, 2011 event. The maximum tsunami amplitude was estimated to be about 1.3 m, with tsunami activity causing strong currents and problems for boaters. One adverse situation occurred when harbor personnel were injured trying to assist docking of several boaters during the strongest tsunami surges. The most significant damage to docks occurred at about 0100 PST on March 12th, 15 h after the tsunami first arrived, when a large surge coincided with the peak high tide. Many other harbors in southern California experienced similar strong surges. This can be seen in Fig. 6, showing the marigram from Santa Barbara Harbor. Dock damage from the 2011 tsunami was estimated to be about $150,000 in Ventura Harbor.

*2.2.1.8 Mission Bay* Similar to what was experienced on February 27, 2010, currents strong enough


Figure 5
Tsunami flow-regime map for Santa Cruz Harbor, from Wilson *et al.* (2012). Current directions and velocities, and areas of sediment erosion and deposition are based on observations of the various (70) ground-level and aerial video, pre- and post-tsunami bathymetry, and sediment analyses

to cause over $130,000 in damage to boats, docks, and harbor infrastructure were generated within Mission Bay. In addition, similar to the Klamath River tragedy where one person drowned, four people (two adults, two children) were knocked off shoreline rocks by strong surges at nearby Ocean Beach. Fortunately, the incident was observed by an off-duty lifeguard, who quickly called for backup from other lifeguards, and all four people were rescued. This situation demonstrated that even an Advisory-level tsunami (less than 1 m amplitude) can cause dangerous conditions to water-front areas.

*2.2.1.9 Shelter Island, San Diego Bay* Whereas during the 2010 tsunami the north end of Shelter Island incurred significant damage, during the 2011 tsunami the south end of the island experienced severe tsunami currents, which caused damage to boats and docks. Dramatic video footage of a police dock at the south end of the island showed a $40,000 police pontoon boat dragged under a dock, damaging the dock and sinking the boat (Fig. 4d). The pontoon boat was tied to the dock perpendicular to the current flow, causing significant drag on the bottom of the boat. Two other police boats tied to the dock had their moorings break, one completely, resulting in minor hull damage when they struck the rock rip-rap along the island.

### 2.2.2 *Lessons Learned*

Emergency personnel for the various coastal jurisdictions were better prepared for March 11, 2011 tsunami because of the lessons learned during the 2009 and 2010 tsunamis, as well as through increased preparedness, planning, exercise, and outreach measures undertaken in recent years. However, a number of issues regarding tsunami hazard identification, education, mitigation, and preparedness still remain unsettled.

- Generally, the same harbors experienced strong currents and damage in both recent tsunami events. This could be related to nearby basin effects, harbor configuration and constrictions, and/or resonant oscillations with the harbors. These potential

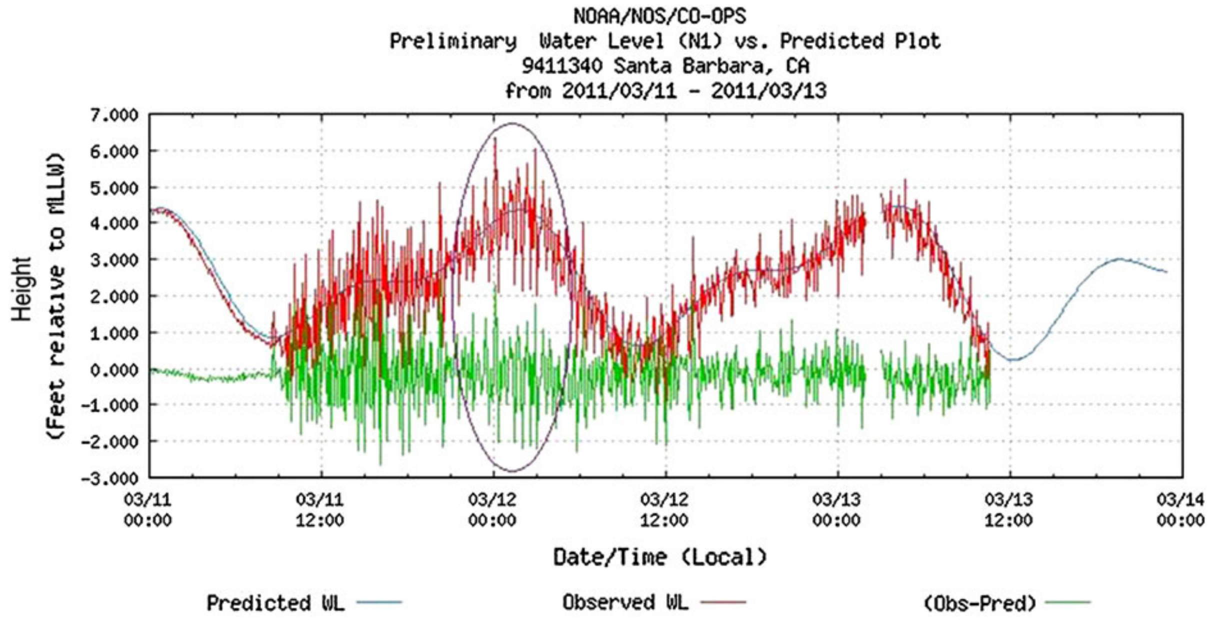


Figure 6

NOAA marigram for Santa Barbara Harbor during the March 11, 2011 tsunami. *Region circled* shows peaks in the marigram that correspond to late surges at high tide, 15 h after first arrival, that may have contributed to damage in Ventura Harbor

causes require further evaluation through high-resolution modeling of these events and analysis of other potential amplification effects.

- Although lines of communication were improved between the various federal, state, and local entities responsible for tsunami response, new gaps in messaging became apparent. For example, erroneous messaging of a much larger tsunami event spread through the Spanish-speaking communities in Santa Cruz and Monterey counties, causing over-evacuation of much of the population to the nearby mountains. On the opposite side of the spectrum, a large section of young people from the English-speaking population gathered too close to the water front despite warnings against entering an area officially declared dangerous, thereby putting themselves in harm's way. Overall, these occurrences indicate that additional, multilingual and multigenerational education and outreach efforts need to be implemented.
- Most county emergency response plans call for full evacuation of their tsunami hazard zones during a Warning-level event. Although all counties within the Warning-Alert area implemented some sort of evacuation within their communities, there were inconsistencies among counties on how evacuations were initiated and what areas were evacuated. These inconsistencies can be attributed to the forecasted tsunami amplitudes being relatively small (1–2.5 m) compared to the evacuation zone within their emergency response plans (typically a 10-m elevation), and the fact that the tsunami arrived during low-tide conditions. Significant variability in forecast (and observed) wave heights along California's complex coastline also contributed to differing response measures taken by emergency managers. For this reason, emergency managers have asked for tsunami evacuation products that can be used in various scenarios, especially during smaller Warning-level events. The state tsunami program will help with this effort in order to provide an accurate and consistent product state-wide.
- Most harbor masters said they were better prepared for this tsunami than in years past, and that the experience and actions of their staff helped save lives throughout the state. Despite this view, virtually all thought there was additional work they needed to do to be better prepared for the next event. After the past two events especially, it has

become clear that even small amplitude tsunamis can cause strong and dangerous currents. Maritime communities need to better understand their in-harbor tsunami hazards (strong currents, eddies, bores, etc.), and know if, when, and where boats should go offshore before a tsunami arrives, as well as when to return. Additional outreach to the various sections of the maritime community (large container/cruise ships, military vessels, fishing fleet, recreational boats) needs to be implemented.

- Maritime communities, most recently in Crescent City and Santa Cruz, have had issues with recovery efforts. Bureaucracy and complications with permitting led to delays in sediment dredging and dock repairs and replacements for these harbors. These delays have hampered getting back to full capacity and generating the needed financial income to promote further recovery efforts. A review of state and federal tsunami recovery protocol is needed to determine where the process can be streamlined and to help develop guidance for impacted communities to improve their resiliency.
- Official Alert bulletins coming from WC/ATWC, while timely, accurate, and detailed, relevant amplitude/arrival data, have had inconsistent formatting issues and glitches in delivery. For example, there was a 1 h gap where the Message 2 Watch bulletin was not received in its entirety through the email alert system. Thus, at the time when Message 3 was issued with the alert level upgraded to a Warning, 2 h had gone by without receiving any textual alert messages from WC/ATWC. These factors tend to add to confusion in the midst of emergency response when time-critical decisions are being made. Delivery of tsunami amplitude and arrival forecasts at more locations along the coast of California, in a more streamlined and consistent format is being coordinated with the WC/ATWC.

## 3. Analysis

The February 27, 2010 and March 11, 2011 teletsunamis were two of the strongest tsunamis to hit the California coast since the devastating 1964 tsunami. Both tsunamis caused millions of dollars in damage to maritime communities in the state. In addition to the lessons discussed in the previous section, we provide the following analysis of forecasted arrival times and peak amplitudes, and evaluation of some of the unique tsunami effects.

### 3.1. Forecast Information

The WC/ATWC is responsible for Tsunami Alert for California. There are two primary tsunami forecast tools available for the WC/ATWC to use to estimate tsunami amplitudes and determine the appropriate level of alert along the coast. The Alaska Tsunami Forecast Model (ATFM) uses pre-computed numerical tsunami models for large subduction zone earthquakes around the Pacific Rim (Kowalik and Whitmore, 1991). Adjustments are made to the ATFM forecasts as observed tsunami information is collected in real-time at tide gauge and Deep-ocean Assessment and Reporting of Tsunamis (DART) stations. More recently, the NOAA/Pacific Marine Environmental Laboratory (PMEL) has developed a tsunami forecast tool called the Short-term Inundation Forecasting for Tsunamis (SIFT) method (Gica *et al.*, 2008). The SIFT system uses both pre-computed deep-ocean model results and real-time inundation model computations near-shore to forecast both coastal amplitude over time and flooding for approximately 50 communities in the Pacific, including 11 in California. SIFT forecasts are adjusted using observational time series data from the DART network to constrain the tsunami source and then provide the refined boundary conditions for coastal inundation forecasts in real-time. A combination of the ATFM and SIFT forecasts were used to determine the Tsunami Alert level for the February 27, 2010 and March 11, 2011 tsunamis for California; the protocol is that the conservative or worst-case forecast between the ATFM and SIFT be used at each location, except if there are outlier values. For the 2010 tsunami, the entire state was put into an Advisory even though one location along the central coast, Port San Luis, was forecasted to be above one meter. For the 2011 tsunami, Point Conception was considered the “break point” between the Warning area to the north and the Advisory area to the south.

An analysis comparing the forecasted and observed tsunami arrival times and maximum amplitudes is essential to understanding and explaining the amount of error in the forecasted values to the coastal communities. After the September 29, 2009 tsunami, Wilson *et al.* (2010) demonstrated that the observed arrival times for the 2009 tsunami were 17–48 min later than predicted. One reason for larger travel time discrepancies in the 2009 tsunami versus the 2010 or 2011 tsunami is that the tsunami was smaller and the initial arrival at many locations was likely obscured by the background noise levels. The average percent error of the forecasted amplitudes in 2009 was ±110 % of the observed amplitudes; "average percent error" is the average of the percent difference calculated by the difference between the forecasted and observed amplitudes divided by the observed amplitude. The higher forecast amplitude errors were likely due to differences between the earthquake source used in the forecast versus the actual source (subduction zone source versus outer rise) and the smaller tsunami amplitudes which lead to higher percentage errors. Also, in the case of 2009 Samoa, one of the WC/ATWC forecast models (the ATFM) could not be used due to a corrupted numerical input file.

Table 1 presents the forecasted and observed tsunami arrival times and maximum amplitudes for the 2010 and 2011 events at various locations along the California coast. The WC/ATWC calculates estimated time of arrival (ETAs) using the shortest tsunami path traveled, which represents the least amount of time for the wave to arrive. Hence, ETAs forecasted by the WC/ATWC tend to be early. For the 2010 tsunami, the forecasted arrival times ranged from 16 min early at Arena Cove to 3 min late at Eureka, with the overall averaged difference in arrival time of 4 min. For the 2011 tsunami, the forecasted arrival times were all early, with a range from 3 min early at Arena Cove to 12 min early at Humboldt Bay and Santa Monica, with an average of 8 min early for the state. These forecasted arrival time values are a significant improvement over the forecasts from the 2009 event.

Figures 7 and 8 show a comparison between the forecasted and observed amplitudes for specific locations from 2010 and 2011 tsunami events, respectively. Observed amplitudes include both data measured from tide gauges to data visually estimated in the field. The forecasted maximum amplitudes from the 2010 tsunami range from 0.54 m overestimation at Santa Monica to a 0.36 m underestimation at Santa Cruz. The average percent error for the forecasted amplitudes is 38 %. For the 2011 tsunami, the forecasted maximum amplitudes ranged from a 0.36 m overestimation at Humboldt Bay to an underestimation of 0.98 m at Sausalito. The average percent error of the 2011 forecast amplitudes is 28 %. Based on the average percent error, the forecasts for the 2010 and 2011 events were significantly better than those for the 2009 event. Despite the relatively good agreement between forecast and measured/observed amplitudes, additional analysis of tsunami signal in the marigrams is needed to confirm the true accuracy of these forecasts.

For the most part, the WC/ATWC forecasted Tsunami Alert levels for the 2010 and 2011 events appear to be appropriate based on the observed maximum amplitudes (Figs. 7, 8; Table 1). The only exceptions would be for the 2011 event, where lower than "Warning" level amplitudes were observed throughout most of the San Francisco Bay area and slightly higher than "Advisory" level amplitudes were observed in Santa Barbara and Ventura, which are south of the Point Conception break-point. The lower amplitude values within San Francisco Bay might support the addition of a new WC/ATWC warning zone separating the interior San Francisco Bay from the open coast.

### 3.2. *Unique Physical Effects*

Although there are clear differences in source location and size between the 2010 and 2011 teletsunamis, there are several physical tsunami effects that deserve further discussion. Both Ventura Harbor and Shelter Island in San Diego Bay had damage in different areas during the different events. Although the Keys section of Ventura Harbor, which has narrow and shallow passages, had significant damage during the 2010 tsunami, there was no reported damage within the Keys during the 2011 event. There are several potential reasons for this: (1) directionality of the tsunami from the south

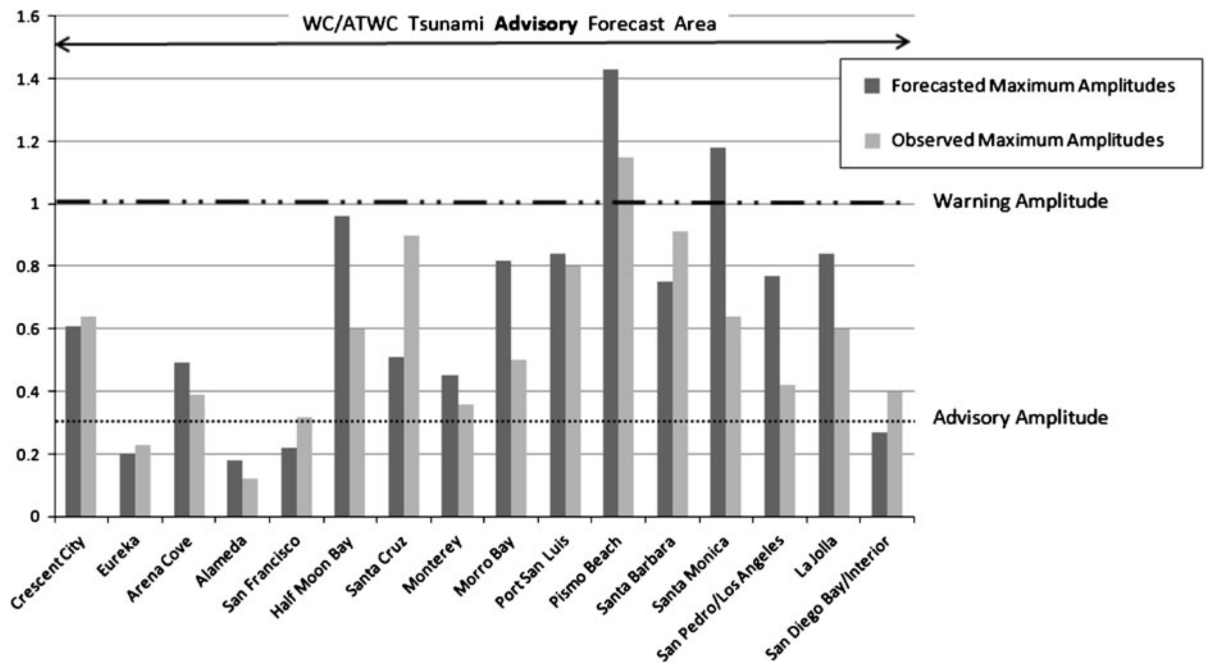


Figure 7
Forecasted and observed maximum tsunami amplitudes for locations in California for the February 27, 2010 event. A tsunami Advisory was issued for the entire state indicating maximum amplitudes between 0.3 and 1 m were forecasted

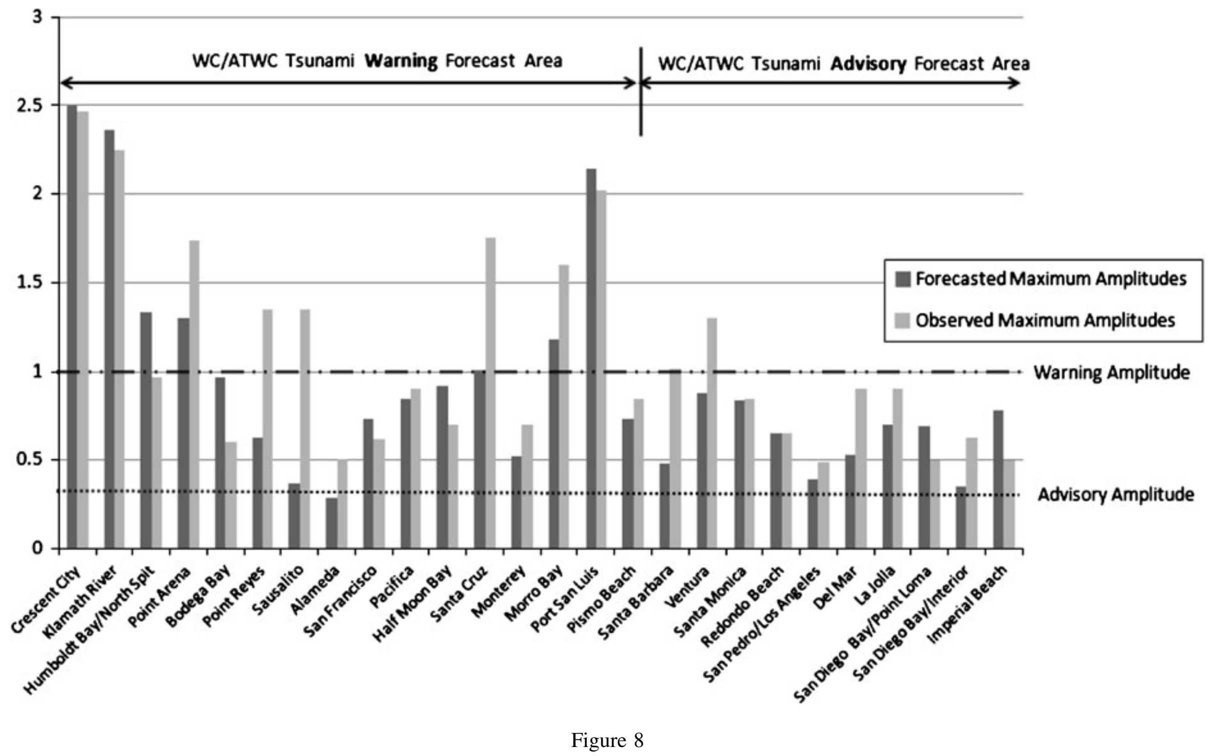


Figure 8
Forecasted and observed maximum tsunami amplitudes for locations in California for the March 11, 2011 event. A tsunami Warning was issues for the area north of Point Conception indicating maximum amplitudes larger than 1 m was forecasted. An Advisory was issued for the area south of Point Conception indicating maximum amplitudes between 0.3 and 1 m were forecasted

during the 2010 Chile event may have focused surge energy more directly into the north part of the harbor where the Keys are located, (2) resonant oscillations could have been generated at different times and different locations, and/or (3) the docks in the Keys that were damaged in 2010 were either replaced or strengthened before the 2011 tsunami. Similarly, the north part of Shelter Island had strong currents and associated damage during the 2010 tsunami, whereas the stronger currents and damage were restricted to the southern part of the island during the 2010 event. The difference at Shelter Island are perplexing because the island is located several kilometers inside the mouth of San Diego Bay, reducing the potential influence of tsunami directionality because it is less exposed to the open ocean. Planned further evaluation of data from nearby tide gauges and detailed numerical modeling might help identify distinguishing patterns in the wave forms to explain these differences.

Another interesting anomaly for the 2011 tsunami was the amplitude spikes that occurred over a 15 h period after first arrival of the tsunami. These spikes are best illustrated in the Santa Barbara marigram in Fig. 6, and are more subtly represented in most of the other southern California tide gauge marigrams. As previously discussed, these tsunami surges were problematic when they corresponded with high tide conditions in Ventura Harbor, leading to unexpected, damaging strong currents 15 h after first surge arrival. Additional work looking at the tide gauge marigrams and the frequency content of the tsunami signal and induced currents might help identify the source for this amplification effect.

## 4. *Future Work*

Although the 2010 and 2011 tsunamis were a challenge for emergency managers and harbor masters, the actions of these groups no doubt helped save lives and reduced property damage. Nevertheless, a number of gaps in tsunami preparedness planning were identified, and will be addressed by the state tsunami program for use at the local level.

There are three primary areas where improvements should be made in overall tsunami warning and emergency response planning. First, because strong tsunami-induced currents caused all of the damage to harbors in California, tsunami warning centers should consider incorporating current velocity estimates into their forecast information provided to states and coastal communities. Second, multi-lingual/multi-generational tsunami preparedness materials must be created and more readily available to the pertinent communities. Since the March 11, 2011 tsunami, the state tsunami program has translated outreach materials into Spanish and other languages. Last, the state tsunami program is producing tsunami planning "playbooks" that have secondary tsunami inundation lines for specific scenarios where there is: (1) a nearby or local source event, where time is of the essence and no forecast has been provided yet, and (2) a forecast is provided with results affecting an area significantly less than the full evacuation zone, as in the 2011 tsunami. The scenarios for time-limited events include a large local event, a large Cascadia Subduction Zone event, and a large eastern Aleutian Island Subduction Zone event. Scenario inundation lines will also be produced for one meter, two meters, three meters, and four meters of tsunami run-up to be used when tsunami amplitudes show significantly less inundation than the worst-case evacuation zones.

The state tsunami program is also working with the maritime community (harbor masters, Coast Guard, etc.) to develop products which can help protect harbor infrastructures and boaters from tsunami hazards. A more detailed analysis of video and marigrams from these tsunamis is underway in order to validate/calibrate current velocities from numerical models, evaluate unique harbor conditions that influence tsunami hazards, and produce hazard maps for the maritime communities (Wilson *et al.*, 2012). In-harbor tsunami hazard maps identify areas of strong tsunami currents for various scenario events that have been previously modeled (Wilson *et al.*, 2008; Barberopoulou *et al.*, 2009, 2011b). These maps aid harbor response activities by showing areas where improved infrastructure is needed, as well as if, when, and where boats should be moved before a tsunami arrives. Offshore safety zones are developed to indicate how far and where boats should go offshore to be safe. Guidance on how to use these maps, as well as a fully integrated outreach plan, is also being developed for individual maritime communities. These products will improve the consistency of overall planning and response activities statewide, producing a more resilient maritime community statewide.

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